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Operations on the National Ignition Facility

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Abstract

The National Ignition Facility (NIF) is a fully operational high energy density physics experimental user facility that focuses 192 laser beams onto a small target at the center of a target chamber. This paper describes how we execute experimental shots on the NIF, both from the user perspective and from the facility perspective. We review the planning processes and tools used to facilitate operations. Safety and radiological aspects of NIF's operations are discussed. We also describe efforts to continuously improve operations and further increase shot rate.

Key words: National Ignition Facility, operations, maintenance

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I. Introduction

The National Ignition Facility (NIF), located at Lawrence Livermore National Laboratory (LLNL), is a laser facility designed to focus 192 energetic laser beams onto a small target located at the center of a 10 meter diameter experiment chamber. The target chamber is equipped with optical, x-ray and neutron detectors to study matter at extreme pressures and densities, providing major new capabilities in the field of experimental High Energy Density physics (HED). In this paper, we describe the experimental operations of the National Ignition Facility, including facility planning and preparations for experiments, operations supporting the experiments, and maintenance of the target experimental systems, laser and support infrastructure. We also discuss how NIF safely deals with the small quantities of certain hazardous materials used in NIF's targets as well as the levels of x-rays, neutrons and other radiation generated by some experiments. Lastly, operational improvements to increase the efficiency of operations are discussed. The NIF Shot Operations Plan [1], in conjunction with the NIF Operations Management Plan [2], the NIF Users Manual [3] and the NIF Maintenance Plan [4] describe the overall operations in detail.

II. Executing Shots on NIF

Operating NIF as a user facility involves two different aspects: (1) definition, review and planning of the experimental campaigns and shots by the user programs and the NIF Director; (2) detailed facility implementation including safety review, configuring the facility and diagnostics, fielding the targets, laser alignment, firing the lasers to the target, and archiving the experiment results. Both aspects are described in the sections to follow.

A. Campaign Planning and Execution by the NIF Users

i. Overview

The NIF, the world's only operational megajoule-class laser facility, is an international user facility supporting several missions including the U.S. Department of Energy (DOE) National Nuclear Security Administration (NNSA) Stockpile Stewardship Program (SSP), national security programs for the Department of Defense (DOD) and other federal offices and agencies, and fundamental science and energy missions for the DOE.

NIF is operated as a user facility in accordance with DOE best practices including peer-reviewed experiments, regular external reviews of performance, and the use of a management structure that enables user and stakeholder feedback. Allocation of NIF resources, including facility time for experiments and development of diagnostic and other new capabilities, is managed using a governance process similar to other DOE science facilities, tailored to meet the mix of missions and customers supported by the NIF.

NIF activities may be broken into two broad categories, namely User Programs and Facility Activities. NIF experiments support the following User Programs:

- *Stockpile Stewardship Program (SSP):* This includes work sponsored by the Inertial Confinement Fusion (ICF) Campaign, Science Campaigns, Directed Stockpile Work, and other NNSA programs in support of the SSP, including the NIF ignition program.
- *Fundamental Science (FS):* This includes work aimed at exploring fundamental scientific questions in materials science, planetary physics, astrophysics, and other areas.
- *National Security Applications (NSA):* This includes national security work in areas other than the SSP, sponsored by agencies such as the Department of Defense (DoD) and the NNSA Office of Nonproliferation (NA-20).

NIF also plays a major role in attracting, training, and retaining the outstanding scientists and engineers required to support the NNSA, DOE, and other missions.

Facility activities support user experiments and long-term sustainment of the facility, and include:

- *Diagnostic and New Capability Development:* Development of new diagnostics and other advanced facility capabilities that support all users.
- *Laser Performance:* This includes calibration shots, frequency conversion crystal conditioning, and efforts aimed at increasing facility efficiency and maintaining 192 beams with the required power, precision, and reproducibility for user experiments.
- *Facility Maintenance and Reconfiguration:* This includes facility and laser maintenance work, diagnostic upgrades, and other activities requiring additional focused time and significant effort beyond routine maintenance.
- *Routine Maintenance:* Typical routine maintenance activities, normally "invisible" to the user community, including exchange of final optics, alignment system calibrations, refurbishment of high voltage switches, regenerative amplifier alignment, information technology upgrades, control system restarts and patching, lubrication of movable/adjustable components (e.g., target positioner drives, roving mirrors, diagnostic insertion manipulator (DIM) motion drives, etc,) and maintenance of the target area systems (e.g., cryogenic systems, target chamber and gate valves, target alignment systems, other). Routine maintenance is performed in parallel with shot operations during the week, and also on weekends with a small operations staff.

The overall shot rate at NIF has been increasing since facility completion in March 2009. There are two types of NIF shots: target shots and laser performance shots. Figure 1 shows the number of target shots/year executed at NIF since 2009.

ii. Allocation of NIF Facility Time and Other Resources

The process for allocation of NIF facility time and other resources is summarized in the NIF Governance Plan. Figure 2 summarizes the process.

The NIF Governance process is overseen by the facility director, referred to as the "NIF Director." The NIF User Office and other elements of NIF facility management support the NIF Director in execution of this process. The NIF User Group, a self-organized group, represents the user community to the NIF Director and other individuals/organizations as appropriate. The NIF User Office is the primary point-of-contact within NIF for User Group issues. Additional detail for the steps shown in Figure 2 is provided below.

a. Call for proposed experiments

The method for solicitation of proposals varies depending on the user program. For SSP experiments, the NIF Director issues a call for proposals to leaders of the NNSA ICF Campaign, Science Campaigns, and other programs. Leaders of these programs work with their staff to determine the set of experiments required to meet program deliverables. This set of proposed NIF experiments is integrated internally so as to be consistent with activities at Omega (University of Rochester), Z (Sandia National Laboratory, Albuquerque NM), and other facilities. The final set of experiments approved by program leadership is then submitted to NIF for review and execution.

A similar process is followed for NIF National Security Applications experiments. In this case, program leadership consists of the members of the Joint National Security Applications Council (JNSAC), a group that includes federal program managers from the DOD, NNSA, and other agencies that support weapon effects, nuclear forensics, and other NIF national security experiments aside from those defined by the SSP. The single call for proposals issued in this area has included a request for information on user funding and hence, has been a joint activity between the JNSAC and the NIF Director. The call is issued to agencies and individual investigators as determined by the JNSAC.

The call for fundamental science proposals is issued by the NIF Director in a manner very similar to other DOE scientific user facilities. The call, issued via the world-wide web, is open to academic, national laboratory and private sector researchers from the US and abroad.

A Principal Investigator (PI) is designated for each experiment and is responsible for representing the proposed experiment through the review process described in Section II.A.ii.b below.

b. Review of proposed experiments

Experiments proposed to be conducted on NIF are reviewed by both the Facility Readiness Committee (FRC) and an appropriate technical peer review panel (PRP).

The FRC reviews all experiments from the perspectives of the capability of NIF to perform the experiment, the operational impact, and machine safety. The FRC examines the following topics in detail: laser performance, targets, diagnostics, operations, target area and laser integrated requirements, simulation needs, experimental and diagnostic Responsible Scientist (RS) requirements, and overall Shot Plan.

Evaluation of required new facility capabilities for each proposed experimental campaign is a key FRC deliverable.

The NIF PRPs review proposed experiments from a scientific and technical perspective. Each of the three major program areas (SSP, NSA, and FS) has an individual PRP tailored to the needs of the specific program. The SSP and NSA PRP review the degree to which the proposed experiment will achieve the specified technical objectives, the qualifications of the Principal Investigator and experimental team, and the uniqueness of the NIF for the proposed experiment. The FS PRP reviews the scientific and technical merit of the proposed work, the qualifications of the Principal Investigator and experimental team, the quality of the proposed work, and the uniqueness of NIF for the proposed experiment.

For SSP and NSA, feedback is provided from the FRC and PRP to the relevant program leadership. For FS, summary PRP and FRC comments are provided to the Principal Investigator of each proposed experiment at the conclusion of the review process.

c. Development of the NIF Facility Use Plan

Upon completion of the review process, approved NIF experiments are integrated into the NIF Facility Use Plan. The NIF Facility Use Plan, developed and maintained by the NIF Director, is a rolling document that describes planned NIF activities over the upcoming 18-month period. The Facility Use Plan describes the time allocated to user experiments, development and maintenance of facility capabilities, and Facility Maintenance and Reconfiguration (FM&R) activities. In addition, this Plan serves as the basis for the detailed facility schedule managed by the NIF Facility and Laser Integrated Planning (FLIP) committee.

The NIF Director communicates regularly with the user community on the Facility Use Plan and other topics via the NIF Experimental Facilities Committee (EFC). The EFC consists of user program and NIF facility leadership and subject matter experts, and provides input to the NIF Director on the Facility Use Plan, future facility capabilities, and other topics as deemed appropriate by the NIF Director and user community.

Execution of the NIF Facility Use Plan as shown in Figure 2 is discussed in Section II.A.iii below.

iii. Execution of the NIF Facility Use Plan

a. Responsible Individuals and Execution Process

An Authorizing Individual (AI) and Responsible Individual (RI) are defined for each approved experiment. The AI is responsible for overall formulation of the campaign and the shot plan and the RI oversees execution of the NIF experimental campaign. The PI may serve as the AI, RI, or both, depending on the nature of the experiment. For cases where the RI is not present full-time on the LLNL site, the NIF User Office may designate a liaison scientist to serve as the RI.

The first step in the process of execution of an approved NIF experiment is an initial meeting involving the RI and key elements of facility leadership. This group identifies the major issues associated with the experiment and in particular identifies the NIF Expert Groups whose approval will be required (e.g., relative to issues such as laser and user optics specifications, impacts to the target chamber/target bay equipment, debris and shrapnel, cleanliness, or hazardous materials). Following this meeting, the experiment is placed on the rolling 18-month NIF experimental schedule. This initial scheduling of the experiment may change as the experimental review process described below proceeds.

The internal NIF process includes the following reviews:

Program Review: The Program Review is led by the AI and is typically conducted approximately six months to one year in advance of the start of the experimental campaign. The primary purpose of the review is to ensure the proposed target design and associated campaign and experimental plan, as informed by input from the expert groups and facility leadership, will meet the designated scientific and programmatic objectives.

Implementation Review: The Implementation Review is led by internal senior NIF staff familiar with the planned experiment and associated facility issues. The review includes members of the NIF expert groups, FLIP, and key members of the proposal team, and examines all aspects of the detailed plan for experimental execution. This review should occur roughly four months before the experiment; the timing of this review depends on the capability and development needs.

Readiness Review: This meeting, led by senior NIF staff, occurs a month prior to the date of the experiment and is the final check to ensure that all preparations for execution of the experiment are complete. All specifications for the setup of the laser, diagnostics, and user optics are finalized at this time. Following successful completion of the Readiness Review, the experiment will be approved for execution by the NOM; the NOM is the final approval authority for all NIF experiments.

Following shot execution, an operations review is performed to identify and address any issues that may have arisen during performance of the experiment. The RI also presents a short post-shot review of experimental results at a weekly NIF update meeting.

b. Data Archiving, Processing, and Retrieval

A primary goal of the NIF is to produce high quality experimental data to validate theoretical physics models and advance programmatic objectives for a wide range of users and missions.

A software tool suite has been developed to acquire and integrate data from multiple sources, including machine state configurations and calibrations, experimental shot data and pre- and post-shot simulations. During a shot, data from each diagnostic with electronic output is automatically captured and archived into a database, which triggers the Shot Analysis, Visualization, and Infrastructure (SAVI) engine, the first automated analysis system of its kind. The engine manages signal and image processing across a Linux cluster and analyzes data from each diagnostic. Results are archived in NIF’s data repository for experimentalist approval and display using the web-based tool, Archive Viewer. Scientists can review data results remotely or locally, download results, and perform and upload their own analysis.

Post-shot data analysis and reporting of laser performance is provided by the Laser Performance Operations Model (LPOM) application. LPOM is directly linked to the Integrated Computer Control System (ICCS) shot database and upon request, can within minutes provide the NIF Shot Director and user a report that compares predicted and measured results that summarize how well the shot met the requested goals (see Figure 3). In addition, the LPOM data reporting system can access and display near-field and far-field images taken on each of the laser diagnostic locations, and provide comparisons with predicted images. More detail on this subject can be found in a companion paper in this issue entitled "Control and Information Systems for the National Ignition Facility".

The NIF Archive database stores all the relevant experiment information—including target images, diagnostic data, and facility equipment inspections, as well as the post-shot state of the facility—for 30 years using a combination of high-performance databases and archival tapes. A crucial design feature of the database, is that it preserves the pedigree of the data—all the linked pieces of information from a particular experiment, such as algorithms, equipment calibrations, configurations, images, and raw and processed data—and thus provides a long-term record of all the linked, versioned shot data. The Archive Viewer application provides researchers secure access to the archive to retroactively analyze and interpret results or perhaps build on experimental data originally produced by other scientists.

B. Facility Implementation of Experimental Operations

i. Laser Operation and Alignment

Laser preparations are specified in the experiment setup. The Integrated Computer Control System (ICCS) configures devices and manages automated setup and alignment of laser components based on the beam usage and requirements of the experiment setup. A wide variety of beam configurations from a single beam to 192 beams is possible. Approximately 60,000 devices must be correctly set and configured for a shot.

The desired laser wavelength and pulse shapes are configured in the Master Oscillator Room (MOR). Quads are distributed into 3 groups, each of which may be set to slightly offset wavelengths, depending on experiments requirements. Each of the 48 quads may be setup with their own pulse shape.

For each experiment, the system is aligned from the Pre-Amplifier Modules (PAM), through the main laser in the laser bays, and to the target using the Target Alignment Sensor (TAS). Most of these tasks are highly automated, with operators intervening when there are issues with processes, or performing verifications. Full alignment of all laser systems to Target Chamber Center (TCC) takes on the order of two hours. Alignment of the target is manual using graphical alignment aids and target metrology, and varies depending on the complexity of the target and experiment configuration. Details on the alignment process can be found in Reference [5].

Prior to each full system shot, one or more PAM "rod shots" are taken. These shots are executed with the system essentially in the final shot configuration, but only the PAM rod amplifiers fire (i.e., the main amplifier capacitor banks/ flashlamps do not fire). This is done to verify the proper operation of almost all systems, and that critical laser parameters such as energetics, pulse shape, wavefront, and timing are correct prior to proceeding with the shot. As part of the rod shot, the target diagnostics complete a dry run to verify their operation and setup. These checks are done both for equipment protection (to verify the system will not be damaged on the full shot), and as a means of ensuring experimental goals are achieved.

Next, the full shot countdown is completed (see NIF Shot Cycle, section II.B.v). After the shot, the main amplifier flashlamps are cooled using clean, dry air to minimize the transfer of heat into the laser, thus minimizing the time until the system is ready to be aligned for the next shot.

ii. Target Operations

Two insertable positioners can be used to hold and align various target types at target chamber center for experiments. The basic target positioner (TarPos) can hold either room temperature ("warm") or cryogenic ("cold") targets (see Figure 4). Cryogenic targets may be cooled to as low 18 K, as specified by the experimenter, using an on-board cryocompressor/cryostat system. Cryogenic insulating shrouds are used to maintain target conditions until a few seconds prior to the shot, when they open to expose the target to the laser beams. Temperatures can be maintained to a precision of a few tens of milli-Kelvin. Target insertion into the target chamber and alignment occur with the shrouds closed. The target positioners provide positioning in 5 axes (within a certain range).

Three gas manifolds provide the capability to fill the targets with low-pressure (a few torr up to about 20 psig) condensable gases, or low or high-pressure (up to approximately 900 psig) non-condensable gases (see Figure 5). Gases used to date include helium (He-3 and He-4), hydrogen (including deuterium), argon, krypton, xenon, propane, deuterated-propane, neopentane, and various mixes of the above. Both a high pressure and low pressure fill can occur simultaneously on a given target of appropriate design. A series of gas purges and vacuum pumpouts are performed to ensure that the required gas purity specifications are met, and that there is no freeze-out of condensable gases in inappropriate portions of the system (for cryogenic targets). As the gas lines between the manifolds and the target are quite long (> 10m) and quite thin (as thin as 10 μm for ignition target capsule lines), this process is quite complicated and can take several hours.

The cryogenic target positioner (cryoTARPOS) can, in addition to the above functions, form and characterize cryogenic layers of fusion-fueled targets. Layer growth and characterization is performed using an in-situ x-ray system with three orthogonal sources/views, while isolated from the target chamber. Development of high quality layers takes several days. Various mixtures of high purity hydrogen isotopes (normal hydrogen (H), deuterium (D) and tritium (T)) can be used. Tritium mixtures are prepared at the LLNL tritium facility per experimenter specified ratios. Then the fuel reservoirs are transported to the NIF and installed in the cryoTARPOS system by cryo operations staff. Typical D-T implosion experiments use reservoirs containing about 20 Curies of tritium gas. More detail on this subject can be found in a companion paper in this issue entitled "Cryogenic Target System for Hydrogen Layering".

Target operations personnel assist experimenters with the specifications necessary to achieve the desired target fill purity and density, and the correct temperature profiles to meet experimental needs. The detailed requirements for each experiment are specified in the shot setup report. In addition, operations personnel manage the gas preparations, target transport, installation and checkout, cooldown and operation of the target and supporting systems during the shot cycle.

iii. Diagnostic Preparations

Over sixty facility target diagnostics of various types (neutron, gamma, x-ray, optical and others) are available for use depending upon experimental requirements. The configuration and setup parameters for each are specified in the experiment setup.

Some preparations require physical configuration in the field to install the correct pinholes and filters, attenuators or to change out complete diagnostics. Three Diagnostic Instrument Manipulators (DIMs) can insert diagnostics to within a few cm of the target. To prevent damage to the instruments, these devices must be equipped with appropriate shields to protect them from target debris, laser light and the x-ray load of the shot.

These insertable diagnostics are normally retracted, isolated from the target chamber and vented for servicing between shots. Other diagnostics can be set up remotely (for example, changing filter, oscilloscope, camera or timing settings). Setup for each diagnostic can vary from several hours (e.g., changing out an insertable diagnostic, see Figure 6) to a few seconds for remotely settable devices. The ICCS verifies that diagnostics are set up as specified in the experiment setup. Insertable diagnostics must be aligned to the target during the experiment as part of the overall alignment sequence.

During the shot, the diagnostics are automatically triggered and electronic data is archived; that data is available to experimenters within a few minutes. For data that is captured on film, image plates or other media (such as activation foils), the hardware is retrieved by operations personnel and processed offline. That data is usually available within a few hours to a day after the diagnostics are serviced.

iv Facility Preparations

For precise operation of the laser system, conditions inside and outside of the laser beampath must be tightly controlled. Most of the laser beampath is either at vacuum, or pressurized with low pressure clean, dry air or argon gas. Argon is used to suppress Stimulated Rotational Raman Scattering (SRRS) that can occur in high power, long pulse lasers and fills the beampath from the exit of the main laser in the laser bay to the final optics assemblies in the target bay. The pressure, temperature and humidity of these gases is precisely controlled and verified for each shot. Similarly, the temperature and pressure of the entire facility containing the laser system is precisely controlled to prevent misalignment of and damage to the laser.

From a safety perspective, most of the operational laser areas must be swept of personnel prior to firing the system shot. The capacitor bays, laser bays, switchyards and target bay must be free of personnel to protect them from potential high voltage, laser hazards and x-ray and neutron exposure. The integrated Safety Interlock System (SIS) is used to ensure that the facility is properly configured for the shot. Personnel are cleared from these areas by a combination of physical sweeps (using “watchman-type” key switches turned by operators), automated announcements, klaxons and warning indicators. Once personnel are cleared of the various areas, the system monitors the perimeter doors, beam stop configurations, crash buttons and other devices. If any device is not in the specified position, the SIS removes permissives from the main capacitor power supplies, preventing amplification in the main laser.

For fusion program experiments that have the potential for producing significant number of neutrons, large concrete shield doors (varying from 0.5 to 2 meters thick and weighing several tons) may need to be closed to provide adequate neutron shielding. See Figure 7 for examples. The required position of these doors depends upon the maximum possible neutron yield from a particular experiment. There are three different configurations of doors possible, depending on the yield. A total of 48 shield doors are installed. Operators close the specified doors, and the SIS ensures the proper configuration of the doors prior to the shot.

v. NIF Shot Cycle

The shot operations team consists of technicians expert in operations of the various subsystems, and they are led by a Shot Director who has overall responsibility for executing the shots.

The ICCS is used to coordinate the execution of each experiment (shot). The highest level of supervisory software, the “shot director” *application*, is a state machine that coordinates the operations of lower levels of supervisory software, and eventually individual devices (via Front End Processors (FEP’s)).

The shot director sequences the shot through several “shot life cycle states” (Figure 8) that have different functions. Upon loading the experiment, the experiment high levels goals and configurations specified in the shot setup are loaded. In “populate plan” the system calculates the required device settings and setpoints (e.g., power supply setpoints, shutter positions, timing settings, attenuator and scope settings, etc.,) necessary to achieve the shot goals. In “implement plan” the system then executes the various tasks to configure the laser and target area systems. This includes things such as pulse shaping, laser sub-system alignments, diagnostic setup and dry runs, timing setup, and alignment of target chamber devices. Each bundle of 8 laser beams, the common resources (such as the MOR and utilities), and the target area systems are managed by lower level supervisory software and coordinated where necessary. Operators perform some functions manually, but most are performed automatically by the ICCS. Tasks are logically sequenced by the system, with individual tasks happening in parallel where possible.

Once the system is prepared for the shot, the system sequences into conducting a PAM “rod shot” sequence, which confirms system setup and performance is acceptable to proceed to the system shot. The data from the rod shot is analyzed by the Laser Performance Operations Model (LPOM) and presented to the Shot Director, who reviews it and approves proceeding with the system shot. If changes are necessary, “update system” is executed and the rod shot is repeated.

After completion of a successful rod shot, the last few devices required for the system shot are configured, and an automated countdown (about 5 minutes) executes the timed activities leading up to firing the laser, including the main amplifiers. Operators monitor the countdown and intervene only if issues occur. Following the shot, laser and target diagnostic data is automatically archived and cooling of amplifiers is initiated. Automated analysis of the diagnostic data is launched, providing most of the initial analysis within minutes.

III. Organization and Processes

A highly qualified and capable staff along with formal processes for executing work is needed to ensure safe operations, both from an equipment and from a personnel safety standpoint. Plans, procedures, practices, and protocols flowing from regulatory requirements have been put in place to manage hazards, such as tritium, beryllium, depleted uranium, neutrons, and associated activation and fission products. The required administrative controls have been implemented through authorizing documents and safety plans, as well as work permits for specific activities at NIF.

A. Operations Organization

The organization that operates the NIF is shown in Figure 9. NIF Operations management has the overall responsibility for the safe, cost-effective, and reliable performance of the NIF.

The NIF Systems Engineering organization supports safe and efficient operation of the NIF laser, A group of functional safety experts ensures the safety envelope of the facility is maintained. The NIF Operations Manager is responsible for the daily planning and scheduling of facility experimental upgrades and maintenance activities.

NIF Site Management is responsible for conduct of operations implementation, standards and policies, work coordination, configuration management, security, safety, hazardous material operations, radiological operations, and training.

Shot Operations is responsible for conducting scheduled shot sequences safely, reliably, and cost effectively. Shot Operations staffs and manages the control room.

Field Operations is responsible for configuring the target area for a shot (installing targets and diagnostics), installing optical components and maintaining the process utilities and facility. Facility Operations and Maintenance operates and maintains the NIF conventional facility and other systems that support laser system operations, as well as provides maintenance management, calibration services, and logistics support functions.

The Laser Alignment, Cryogenic and Target, and Target Diagnostics organizations are responsible for the maintenance and operation of the technical equipment within the NIF, ensuring that systems are performing safely, cost effectively, and reliably, while meeting technical requirements. They work closely with NIF Engineering and Systems Engineering to ensure that systems meet performance requirements, implement upgrades, and improve availability and reliability.

B. Work Planning and Execution

As shown in Figure 10, the work planning and execution process has various time horizons. Planning activities in the 6 month to 2 year horizon focus on ensuring readiness for major facility maintenance and improvement periods. These are planned sufficiently far in advance to support shot planning and integration with the maintenance periods.

In the 6 month to 8 week window, the work planning focuses on the next milestone, or maintenance period, while ensuring that less impactful maintenance is appropriately prioritized and coordinated with shot operations.

Near term (7 days or less) work planning and execution rely on the working group planners working with the work center supervisors to allocate resources and coordinate among the working groups and shot operations to de-conflict work. Their roles are described below.

Department Planner: The Department Planner for each area is responsible for understanding the maintenance and other work that needs to be accomplished. The Department Planners gather this information from the system managers and the computerized maintenance management system (see section IV.D), where applicable. They chair the weekly planning meetings and work with the working groups to prepare maintenance window packages and present them for scheduling.

Work Center Supervisors: The Work Center Supervisors know the resources (labor, time, and equipment) required to perform work. They work with department planners to prepare resource-level weekly plans and allocate the labor to support the daily work plan. They are responsible for reviewing work permits for scope, hazards, and controls and ensuring that work is safe, well planned, and ready to proceed.

Field Supervisors: The Field Supervisors are in the field supervising the technician teams assigned to their areas. They work with the Work Center Supervisor to develop daily work plans and make the daily job assignments. They also conduct the shift turnover meetings (prepare reports and distribute).

The Daily Operating Schedule Team is comprised of Work center Supervisors, shot operations and work control staff. They compile all the activities that are either required for execution of experiments on NIF, or could interfere with the conduct of the experiments. See an example in Figure 11. It provides in a single location, both an overview of the week's facility activities, and a detailed list of critical path tasks and their contribution to upcoming shot operations.

C. Work Control

Every activity at NIF goes through a review and approval process, from the operation of the main NIF laser all the way down to maintenance tasks. The work authorizing document, the Integration Worksheet (IWS)/ Job Hazards Analysis (JHA) guides the conduct of this process. Work tasks are evaluated, the associated hazards are analyzed and specific controls for each task are identified. In some cases, an Operational Safety Plan (OSP) may also be needed. An Operational Safety Plan (OSP) is a more detailed safety review of certain activity hazards. A tiered approach to hazard mitigation is employed with options that may include engineering controls (e.g., interlocks, alarms, and shielding), administrative controls (e.g., procedures and signs), and personal protective equipment (e.g., gloves, safety shoes, and respirators). Detailed controls for specific work tasks are flowed down from the safety documents, specified in detail, and approved through the use of work Permits.

Work that is executed on the NIF has to be properly planned and coordinated. The NIF has a challenging set of work activities and operations requiring a higher level of coordination than traditional, smaller laser facilities. Work must be fully evaluated for its impact on other scheduled activities, including target shot operations.

D. Cleanliness Protocol

Cleanliness of optics inside the NIF beampath is critical to maintaining overall availability, as significant optic damage can occur due to the high laser fluences experienced at NIF. Considerable effort is employed to ensure that the inside of the beampath is maintained. Both particulate cleanliness and Non-Volatile Residues (NVRs) are important for NIF optic lifetime. Purge gases that supply the NIF beamline are maintained at Federal cleanroom Standard 209E Class 1 (ISO-3) levels. Beampath interior surface contamination levels are in general maintained at Level 100 A/3 or better (per MIL-STD1246C). Materials used in the beampath must pass off-gassing tests as well as particulate cleanliness testing.

When the beampath must be opened for maintenance, local cleanroom conditions are established. This includes: use of only approved materials, cleanroom garb, cleaning of the area, either positive clean air purge from the beampath or local HEPA ventilation, and air sampling. The protocols result in the work area meeting Class 100 (ISO-5) or better cleanroom conditions. In addition, the amount of time that the beampath is opened is minimized using a maximum ‘class-hour’ protocol. These measures have been found to be very effective in meeting NIF optics performance goals.

While the target chamber environment is by necessity not as clean (due to target debris), controls are still in place to ensure that anything exposed to the TC environment is at least gross cleaned, and materials must be on the approved NIF materials list for this application. This ensures that deleterious materials are not present that could be damaging to either the final optics or other diagnostics or targets.

E. Training

Only knowledgeable and trained workers are authorized to perform work. A detailed training and qualification program has been developed and implemented to ensure that workers understand the hazards and controls associated with their work and are qualified to work safely in the environment at NIF.

The NIF Operations training philosophy is to maintain a standardized, proactive training posture to develop and expand the level of expertise of the workforce and to establish uniform standards of safe operation, and ensure workers are competent to perform all assigned task

Training methodology may consist of web-based classes, instructor-led classes, or on-the-job training, often referred to as Qualification Cards. All training course completions are tracked in LLNL training database (LTRAIN).

F. Configuration Management

Configuration Management (CM) is an integrated management system to maintain the relationship between requirements, data, execution, and the physical/functional configurations. This involves the systematic identification of NIF hardware configurations and the management of changes to those configurations. The term “configuration” encompasses not only the physical items delivered but also the controlled safety and performance requirements and criteria that those items have been verified to satisfy.

NIF uses a number of computer tools to assist in the implementation of configuration management; these are Enterprise Configuration Management System (ECMS), Location Component and State tracking system (LoCoS), and the Campaign Management Tool (CMT). See the following section for more information regarding these tools.

The NIF configuration management process is applied in a graded manner. Those elements related to public safety, worker safety, the environment, significant programmatic impact, and Safety Basis administrative controls are “special” configuration items (CIs) and undergo more rigorous review than those that support functional requirements and facility functions.

G. Tools

Several software tools are used routinely by NIF operations personnel and are critical to successful day-to-day operations of the facility. These fall into several categories:

- Production, assembly, test and inventory control of parts and Line Replaceable Units (LRUs)
- Installation/removal and condition, status and configuration of installed parts and LRUs
- Work management, such as Work Permits, task scheduling, and problem identification, tracking and disposition
- Optics damage monitoring and management
- Verification that facility configuration matches that requested for a specific experiment
- Shot specification and scheduling

A combination of commercial software tools and in-house developed tools are required to meet these varied needs. Some of the key tools use at the NIF are summarized in this section.

Archive Viewer. The interface that allows NIF personnel and visitors to view data from the NIF data repository as a dashboard or in tabular form, or to download data to process offline.

Campaign Management Tools. NIF personnel and experimenters use the Campaign Management Tools (CMT) to generate the laser and facility configuration required for an experiment. CMT is a suite of software applications designed to translate experimental plans and specifications into actions required by the control system to execute the shot.

Configuration Checker: A tool used by NIF shot operations to ensure that the hardware configuration of the NIF laser and target area systems meet specified experimental configurations. This includes things such as verifying that specified targets, diagnostic filters, and user optics are installed.

Enterprise Configuration Management System (ECMS). ECMS provides industry standard best practices for Engineering Change Requests (ECRs), Engineering Orders (EOs), work flows for review and release, and a document vault. Disposition of hardware is part of the ECR process; material in process, inventory, and/or installed are all addressed.

NIF Location Component and State Tracking System (LoCoS) is a custom built web application built to support the work activity of all parts of the NIF organization; work authorization, problem and conformance reporting, laser system and diagnostics status for operational readiness, LRU installation transactions and inspection/metrology data sets. NIF personnel use the web-based Location and Component System (LoCoS) to track installed parts from the facility level down to individual parts. With more than 6,000 LRUs, knowing exactly what part is installed and keeping track of its history and configuration data is critical. It also captures and manages calibration data for target diagnostics, targets, and parts. Much of this data is used either by the control system to properly configure the system for the shot, or to automatically analyze the resulting shot data. LoCoS also provides simplified user interfaces to other tools (like Glovia) for commonly performed functions. A screen shot of LoCos is provided in Figure 12.

Production Optics Reporting and Tracking (PORT) provides specialized data aggregation, reporting and selection functions for the optics and target production processes. Also includes functions to manage tasks for work teams.

Glovia Enterprise Resource Planning is a commercial product configured and customized as the system of record for parts, serial numbers, bills of material, assembly/installation/removal transactions and provides visibility into the location and status of key optical, target and diagnostic components. This is the primary tool to manage parts and assembly of optics, targets and diagnostics. This tool also allows retrieval of full histories on serialized parts and LRUs, from vendor inspection reports, through warehousing, processing, assembly, installations and removals.

NIF Wiki. The NIF Wiki was created as a tool to improve collaboration and communication amongst the scientists using NIF. It provides a single, central location for quickly storing and accessing a diverse set of information and knowledge related to experiments. The wiki stores user-generated content in a free-form format (presentations, documents, tables, charts, etc.). It is closely coupled to NIF's data repository. This connection enables users to navigate quickly and easily between official shot data and scientific analyses and interpretation. Primary features of the NIF Wiki include the shot log, shot pages, campaign summaries and performance charts, meeting pages, and presentations.

Shot Clock. The Shot Clock (Figure 13) allows NIF personnel and visitors to monitor the progress of the experiment as the NIF control system implements the experimental parameters defined in the CMT.

IV. Maintenance

The reliability of the NIF, including its support systems and utilities, is essential to ensuring that NIF is available to support laser operations. The *NIF Maintenance Plan* [4] describes the system's equipment and assets, boundaries, interfaces to other systems, and the maintenance approach, including failure modes and general responses for major system off-normal conditions. The NIF maintenance strategy has been to perform preventative, corrective, and reactive maintenance on all systems as appropriate to best maximize facility availability. Each system is evaluated to ensure the best combination of these types of maintenance is applied to maximize system shots. This maintenance strategy has worked well because predictive and condition-based (vibration monitoring, thermal imaging, oil sampling, etc.) maintenance strategies have been added for many systems. Maintenance is scheduled and performed between shots as much as possible.

The goal of the NIF Maintenance program is to achieve a reliable, available, and maintainable (RAM) facility. A reliability-centered maintenance (RCM) program was recently deployed to reduce failure rates and the time required to repair equipment, anticipate problems before they occur, respond faster to failures (by having parts, permits, and procedures ready), and plan for windows of opportunity. [6] Using the RCM process to decide where to focus maintenance resources has allowed NIF to:

- Identify and focus on shot-critical functions.
- Determine critical failure modes and impacts.
- Strategically apply health monitoring tools to anticipate problems.
- Evaluate the most cost effective mitigation to preserve functions.
- Tailor tasks based on impact to shots.

A. Maintenance Plans and Procedures

System-level maintenance plans (SLMPs) detail the approach and methods designed specifically for each of NIF's approximately 160 systems. The SLMPs are developed based on RCM principles, with a focus on maintaining functional requirements for each system. The RCM process begins with a system functions determination and then proceeds with a Failure Modes and Effects Analysis to determine critical failure modes and their impact on shots; it concludes with a determination of the most cost-effective mitigation to preserve functions. Results from the RCM process lead to a tailored set of tasks based on the system's importance to shot functions.

In nearly all instances, procedures are required when performing work on NIF's systems and are provided for all maintenance being performed under the following conditions:

- High consequence of failure: When failure to correctly perform a specific sequence of steps for an activity would likely result in high consequences to the system, environment, safety, and health.
- Complex work activity: When a work activity is so complex that authorized and qualified workers may not successfully and safely complete it without a procedure.
- Infrequent Performance: When moderately complex activities are not routinely performed.

B. Maintenance Periods

To better plan and coordinate maintenance activities with shot activities, NIF has defined the following maintenance categories:

- Type 1: Maintenance activities that are integrated with shot operations with the work usually completed in one twelve-hour shift.
- Type 2: Maintenance activities that can be completed in less than six twelve-hour shifts (less than three days) with some effects on shot operations, depending on details of the specific activity.
- Type 3: Maintenance activities that take longer than six twelve-hour shifts (more than three days) to complete significant facility maintenance and reconfiguration activities. During Type 3 activities, shot operations will be significantly affected.

The maintenance periods are coordinated with Shot Operations starting with the high level shot plan. The maintenance activities are fully integrated into the daily operations schedule, and potential conflicts among maintenance activities and shots are de-conflicted at twice-daily plan of the day meetings—one for day shift and one for night shift.

C. Spares

Adequate spares are available for maintenance. For the laser systems, initial spares have been defined and are continuously updated based on operational failure rates; NIF aims have at least one full spare for every critical item. NIF facility availability has rarely been impacted by spares unavailability during any of the previous years of operation. The process for determining spares involves incorporating modeling results based on current operational experience of failure rates and recovery times. Optics production has been calculated based on the shot plan.

For conventional facilities and utilities, spares are set based on the RCM analysis. For these systems, often there is a large degree of redundancy. In these cases, spares are minimized and replacements are ordered upon failure. Exceptions to this rule are items with a very long lead time or items that have a very large impact to shot operations (e.g., vacuum pumps).

D. SMaRT

The Systems Maintenance and Reliability Tracking tool (SMaRT) is the computerized maintenance management system based on the INFOR product that contains information to enable the processes necessary to perform maintenance on NIF subsystems. SMaRT tracks work that is performed and retains the records of work performed.

For conventional facility and utility systems, each maintenance activity is described by a work order. Each work order proceeds through a review and approval process prior to being executed in the field. Typically each work order contains a maintenance procedure detailing the work activity. In addition, when material is required to perform the activities, the work order contains a material list. This material list is tied to our inventory management tool, Glovia, to facilitate ordering, storage, and kitting of required spare parts.

Each work order undergoes a close-out review where data from the field and booked hours are captured. In addition, various data fields are set or completed during the close-out process to enable sorting of data for RAM analysis or other metrics.

The SMaRT tool assists in RAM analyses. SMaRT provides a means of tracking hours between failures and repair times to provide mean time between failures and mean time to repair. In addition, by using failure codes at the equipment level, one can track common failure modes and identify common quality issues.

E. Maintenance Organization

The NIF organization assigns responsibility for various systems to a system manager. A system manager typically is responsible for several like systems. The system manager is responsible for:

- Understanding performance requirements for their system, including all safety aspects.
- Creating the SLMP that defines the maintenance required for that system.
- Directing the work by first defining the work through maintenance procedures and work orders.

Often the system manager will be in the field to guide the technicians; this is especially true for first-time activities, activities with a high level of consequence, or activities that happen rarely. Because the system manager's responsibilities span multiple systems, often a system manager will have a helper. The helper is typically an engineering associate, while the system manager is a degreed engineer.

The system managers are supported by a team of trained technicians. The technicians work out of a pool managed by the work center supervisor. Typically, the technician team is split into multiple shifts in order to support the 24/7 operations of the NIF. The system manager works with the department planner to schedule the work activities by deciding in which week to "bucket" work. Then the department planner and the work center supervisor create a detailed weekly schedule assigning technicians by name to the activities.

There is also a small integration group that assists all system managers. The integration group owns the SMaRT tool; SMaRT administrators in the integration group assist the system managers in setting up their preventative maintenance program in SMaRT. The integration group is also home to condition-based maintenance tools such as vibration analysis, thermography, oil sampling, and ultrasonic monitoring. As it is not practical to have each system manager to become proficient in all of these tools, the expertise resides in the integration group and is a resource for all system managers. Finally, calibration, another activity that cuts across all systems, is part of the integration group.

V. Safety and Radiological Aspects

The hazards associated with NIF and its operation have been identified and evaluated since the earliest stages of design, and safety features have been incorporated into the design to mitigate these hazards. The bounds of NIF operations are described in the National Environmental Policy Act (NEPA) documentation [7,8]. This NEPA documentation ensures that a thorough evaluation of the impacts of NIF operations has been completed, and that the risks to the public and the environment are understood and communicated.

The limits specified in the NEPA documentation are flowed into NIF's Safety Basis Document (SBD). The SBD provides a more detailed identification and assessment of hazards, resulting in additional controls to ensure that risks to co-located workers and the public are low. In addition to flowing down fusion yield and inventory limits, the safety basis document has identified a set of credited safety systems (e.g., radiation shielding) and other credited administrative controls that govern NIF operations. NIF also utilizes the IWS/JHA/OSP (see Section III.B) that evaluates the safety of operations at the worker level, identifying specific controls associated with facility hazards.

A. General Safety Issues

A variety of safety issues exist at the National Ignition Facility. These have been evaluated in detail and mitigations have been put in place to control the hazards. A summary of the key hazards at the NIF, their sources and typical mitigations is provided in Table I.

The goal of the safety program is to provide a safe and healthy work environment for employees and visitors. A full-time staff of highly skilled environmental, safety, and health (ES&H) professionals (health physicists, environmental analyst, safety engineers, industrial hygienist, health and safety technicians, and administrators), led by an ES&H Manager is available at NIF. This team's role is to develop, monitor, and ensure safety and regulatory compliance of NIF operations. The importance of safety is embraced at all levels of NIF and ranks above all other aspects of our operations, including schedule and production.

By embracing safety as a value, the NIF organization has been able to achieve an excellent safety performance record. The Total Recordable Case (TRC) rate has been maintained well below one for years. NIF has been recognized for its excellent safety performance by the National Safety Council.

B. Radiological Operations

NIF safety documentation describes the hazards and provides controls for managing radiation hazards and radioactive material used in NIF targets during operations. Radiological hazards include radiation generated during shots, and radioactive contamination from tritium in fuel as well as radioactive by-products from a shot. The radioactive environment can also impact equipment, limiting its performance or lifetime. This section summarizes some of the key aspects of NIF radiological operations.

i. Radiological Safety

Shots on the NIF may generate prompt radiation. This can range from x-rays only, if the lasers impinge onto a metal target, to a burst of prompt neutrons and gamma rays for deuterium-tritium fueled capsules. For the highest yield shots anticipated on NIF, about 7.1×10^{18} neutrons will be produced, corresponding to 20 MJ of total fusion energy. This energy is released over times of less than 1 ns, so the power level is extremely high. The fusion energy is primarily (80%) carried by energetic neutrons. These energetic neutrons interact with materials in the target and in and around the target chamber. Some of the interactions lead to activation of these materials producing radioactive species that subsequently emit ionizing radiation (primarily beta particles and gamma rays) as they decay.

Anticipated radiation levels in and around the facility have been studied in detail. [9, 10] Figure 14 presents a prompt dose map of the anticipated radiation levels (neutron and gamma) within the NIF for a 20 MJ shot (note that this level of yield has yet to be achieved on the NIF). This is a plan view of the facility, with the Target Bay (TB), Switchyards (SY), and Laser Bays (LB) identified. This dose map illustrates the estimated dose values at ground level of the facility. Doses in the SYs are significantly less than in the TB due to the mitigating effect of the thick shield walls and doors. There are some localized areas of higher dose in the SYs due to radiation streaming through penetrations in the TB-SY wall. There is also streaming from the SYs into the LBs through the beam tube penetrations in the SY-LB wall. The TB, SYs and LBs are exclusion areas during these types of shots. There is significant shielding around the facility that mitigates the dose from a shot in occupied spaces both inside and outside the facility to less than 50 μSv.

Material in the target bay is subject to neutron activation, and there will be a decay radiation field that persists for some time after a shot, depending on the shot yield. Many components within the facility contain aluminum or aluminum alloy, so the radiation field decays at a rate generally determined by Na-24, one of the dominant radionuclides produced in aluminum (14.97 h half life). Several days after a 20 MJ shot, the dose rate in most spaces within the TB is expected to fall below 50 μSv/h, the level of a Radiation Area. Figure 15 is an example of a decay radiation dose map. A few localized hot spots are evident. These are tips of entrant devices that were inside the target chamber at the time of the shot, shown pulled back into their vessel as would be the case after a shot. The hot spot could be the remnants of the target that will need to be changed out, or the snout of a diagnostic that will need to be removed. Workers would be exposed to low levels of radiation while performing these tasks. The goal for worker doses is to maintain them As Low As Reasonably Achievable (ALARA). This is accomplished by mandating a stayout time after high yield shots, tightly controlling access to the Target Bay (TB), planning work in the TB to be efficient so that task durations are minimized, and carefully monitoring the doses of those who have entered the TB.

Once experiments that produce high yield have begun, managing worker dose will require attention by both the health physics staff and line management. While post shot stay out times will significantly reduce dose rates for workers entering the TB, workers will continue to be exposed to low dose rates during routine operation. A typical worker might spend 4-10 hours per day inside the TB, and even with relatively low general area dose rates of a few to a few tens of μSv/h, cumulative doses could become significant if not closely controlled.

The web-based application tool NEET (NIF Exposure Estimating Tool) is used to help plan for work in these low-level radiation fields. Specific tasks can be evaluated based on the task location and time after a specific shot or series of shots, and decisions can be made to defer tasks or figure out how to reduce task durations. Local shielding can be considered, but in most cases is not practical due to the general area radiation field and the dose that would be incurred to install and remove the shielding.

In more general terms, as shown in Figure 16, NEET is used to develop annual ALARA plans and set administrative dose limits for workers and work groups. To develop the annual ALARA plan, an estimate of experiments planned to produce significant yield is obtained. The approximate yield and experiment dates are entered into NEET. At that point, the predicted localized dose rates throughout the TB can be computed. Each work group provides estimates of their routine tasks, where they are located, how many workers are involved and the frequency or number of times the task is to be executed during the year. NEET is used to obtain representative dose rates for each of these tasks, assuming a typical entry pattern between shots. This data is entered into a spreadsheet that then produces the expected annual dose for the work group, and the average worker dose within that group. These are used to set the goals and administrative control limits for the year. The assumptions that went into developing these estimates (such as average dose rates at re-entry) are then included in the work controls for those tasks. Work controls are flowed down to the individual Radiological Work Permit (RWP) that supplements the regular Work Permit for that task.

Another radiological issue to manage is the dispersion of radioactive material within the target chamber and associated systems. This contamination derives from unburned tritium, as well as activated material from the target, or ablated activated material from the chamber or devices entrant in the chamber. Also expected are some fission products from the Depleted Uranium (~ 40 mg) in the target's hohlraum. The NIF confinement envelope and contamination control systems work to confine the contamination created from the NIF shots. The Confinement Envelope consists of the vacuum or pressure boundary of components in a large number of subsystems (e.g., Final Optics Assemblies (FOAs), diagnostics and positioners (e.g., CryoTARPOS), vacuum systems) that are connected to the target chamber and have the potential to receive contaminants directly from the target chamber. These components, by virtue of their boundary function, act to "confine" hazardous and radioactive contaminants and prevent release to the adjacent occupied spaces of the NIF. The contamination control systems receive contaminated gas streams and equipment from the confinement envelope and confine and process the contaminants. This includes vacuum pump exhaust piping that is routed to the Tritium Processing System (TPS), or to the stack. Other elements of the contamination control system include enclosures: room-within-a-room enclosures that provide additional confinement of contamination, fume hoods for handling and storing contaminated material, and a number of specialized containers, including cabinets for purging optics of residual tritium, transport carts for moving diagnostics from the target chamber to refurbishment areas nearby, and containers for transporting tritium gas and tritium-containing targets to and within the NIF. One of the challenges for the NIF is that regular access to contaminated volumes is needed to perform routine operational activities, such as target change outs, diagnostic change outs, and other maintenance activities. These operations have been successfully completed by application of standard contamination control practices, using ventilation, Personnel Protective Equipment (PPE), draping, defining contamination areas, and monitoring. More detail on NIF Radiological operations can be found in References 11, 12 and 13.

ii. Fuel Gas Management

An isotopic mixture of hydrogen is the basic fuel for fusion/ignition targets. The physical form of the hydrogen fuel prior to the shot is a thin hydrogen "ice" layer within the precision target capsule. The quality and safety of the shot is, in part, ensured through the fuel gas supply, handling, and analytic systems that prepare and quantitatively determine and maintain the key attributes. For the NIF, isotopic mixtures of hydrogen gas are prepared and analyzed at the LLNL Tritium Facility and subsequently transported in fuel reservoirs to the NIF.

The capsule is nominally 2 mm in diameter containing a hydrogen ice layer of 60 μm. Once installed and connected, fuel is admitted to the capsule from the reservoir through a 5-μm glass fill tube. At fill time, the capsule is cooled to the condensation point for the isotopic gas mixture, and fuel is added to the capsule as a liquid. The amount of liquid is precisely controlled to provide the proper thickness of the resulting solid hydrogen ice shell.

Depending on the experimental objectives for a given shot, the isotopic composition of the hydrogen fuel gas may be adjusted for maximum deuterium/tritium (DT) fusion yield, a 50/50 mix, or it may use a mixture normal hydrogen and tritium with a small amount of deuterium (THD) to suppress the neutron yield. As the formation of a single crystal of hydrogen ice is required for a smooth, highly spherical hydrogen ice layer, the fuel gas must be free of contaminant gases. An x-ray imaging system is used to monitor and control the formation of the ice layer. An example of an image of an ice layer is shown in Figure 18. More detail on this subject can be found in a companion paper in this issue entitled "Cryogenic Target System for Hydrogen Layering".

High levels of contaminant gases, like nitrogen, argon, water, and methane, can lead to defects in the ice layer as it forms. In addition, ingrowth of ^{3}He, the decay product from tritium, must be managed. Isotopic and molecular determination of the fuel gas constituents, including trace impurity gases, is accomplished with a sector magnet mass spectrometer and associated gas handling and sampling system. Example specifications for fuel gas are shown in Table II.

The fuel gas mixtures are prepared in either of two gas handling systems at the LLNL tritium facility: the Tritium Science Station, and the Tritium Processing Station. These systems each include two sets of uranium-hydride and palladium-hydride “bed” pairs to serve as sources of pure tritium gas or prepared mixtures of tritium with deuterium and/or normal hydrogen. And, each station includes a separate uranium-hydride bed to capture and hold residual gas left over from the gas preparation process as well as unused gas returned from target operations at NIF. This “scrap” is later recovered and returned to Savannah River Site for purification and recovery of the tritium. More details on the fuel gas management process can be found in Reference 14.

iii. Radiation Damage

A deuterium-tritium (DT) target shot will generate primarily 14 MeV neutrons that propagate outward from the center of the target chamber. The neutrons pass through the chamber wall and into the Target Bay with multiple scatters resulting in a high fluence, broad energy band of neutrons and gamma rays. When the scattering process results in energy deposition into materials, the deposited energy can lead to permanent changes resulting in damage to that material. Several infrastructure support systems will be exposed to the high yield shots over the facility’s 30 year life span. During the shot, the scattering neutrons will interact with various electronic components located in the Target Bay potentially causing operational concerns including “upsets”, (memory corruption in electronics, communication errors, false alarms) and permanent damage to a subsystem.

The Target Bay contains many facility systems that require some sort of mitigation to address the radiation environment. Examples of equipment that are exposed to neutrons, include but are not limited to, the positioners, diagnostics, alignment instruments, monitoring systems, seals and o-rings, optical fibers, optics, motors, air handling systems and safety systems.

In response to this potential radiation exposure, analysis and testing of several facility safety systems have been conducted to establish management guidelines for these systems. The guidelines include operational risk based on location, sensor longevity, and conduct of operations for each safety system. A unique type of mitigation has been identified for each system or component. The major goals of the mitigation strategy are to increase the longevity of the subsystem, allow for the subsystem to be operational during a shot (if appropriate), and to allow for easy replacement of the subsystem, if damaged. The mitigation plan establishes “upset” and “damage” levels for the NIF systems and requires that action be taken before the “upset” level is reached to assure continued reliable operation.

Detailed Monte Carlo radiation transport calculations were performed to establish the expected radiation field in the Target Bay. Then, based on instrument locations within the Target Bay, an estimate of the local dose levels in which the system would be expected to operate was known. The shot history of a system is tracked and cumulative dose levels are monitored and compared to the expected levels for upset and damage. Based on this comparison a system can be managed though an operational plan. Examples of mitigation strategies that could be included in an operational plan are provided in Table III. More details on management of NIF equipment in a radiation environment can be found in Reference 15.

VI. Review of Performance Metrics and Operation of NIF as a User Facility

Annually, NNSA and the Lawrence Livermore Laboratory assess performance of the operation of the NIF as a user facility using established contract performance evaluation processes. The evaluation process includes a review by the NIF Directorate Review Committee that reports to the laboratory Director. These reviews include consideration of the user facility metrics. NNSA performs periodic external reviews of operation of NIF as a user facility in a manner similar to DOE Office of Science user facilities.

VII. Continuous Improvement Efforts

The most important challenge for NIF as a User Facility is to increase the number of user shots while maintaining the safety and quality of the operations, and while reducing the operating cost and improving efficiency.

The number of shots that can be executed is the product of time available for shots divided by the average duration of a NIF shot. We are increasing the time available for shots on NIF by optimizing the maintenance process and reducing the time needed to shut down operations to commission new capabilities for the facility. We also have an active effort to measure the shot cycle and implement engineered shot cycle reduction and reliability improvement projects, staffing optimization and process improvements.

Previously, we operated on a commissioning and construction schedule that used to only fire the facility at night, with day time allocated to construction, installation, and maintenance. We are now moving to a five day shot period per week, dedicated to back to back shot operations with a dedicated two day maintenance period. Facility maintenance is being optimized using the Reliability Centered Maintenance approach [6], focusing the overall preventive maintenance effort and adding redundancy for critical systems such as the cooling system for NIF's 1000 electronic equipment racks. Working with field supervisors and technicians to get feedback and recommendations on maintenance cycles has saved hundreds of hours a year by eliminating unnecessary maintenance.

We are reducing the shot-to-shot cycle time by evaluating and optimizing each shot task and sequence and improving activity planning by developing an integrated shot and facility planning schedule that maximizes facility availability and minimizes diagnostic and optics reconfiguration. A new shot cycle metrics process for control room activities has been implemented to collect data on each shot step, including delays and problems to make additional improvements to shot cycle efficiency.

We have established a three pronged approach to improving the shot rate on NIF:

- Consolidate facility staffing so we can swarm reconfiguration activities in between shots;
- Implement a series of engineering projects to speed up the shot cycle by hardware and software changes;
- Reduce the impact of equipment failures by a targeted equipment reliability improvement effort that includes improving redundancy, spares, and training.

These activities were formalized and extended in a congressionally mandated "120-day study" to improve the NIF shot rate in the FY2014-2016 period.

Now on the path to mature operations, NIF continues to evaluate and improve processes and capabilities, with the goal of maximizing availability, efficiency, and facility access while preserving safety. Initial facility controls were deliberately very conservative, but with a trained and stable workforce and roles, procedures, and protocols in place, controls are now being revised to be commensurate with our current understanding of the impact of hazards and reduce unnecessary overhead burden. Examples of recent efforts to revise facility controls include automated facility sweeps used prior to firing a laser shot, optimized radiation and contamination controls, and the use of simplified equipment safing procedures (LOTO).

References

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Footnotes

[a] Total Recordable Case Rate is a measure of the recordable workplace injuries (more serious than First Aid), normalized per 100 workers per year, or per 200,000 worker-hrs.

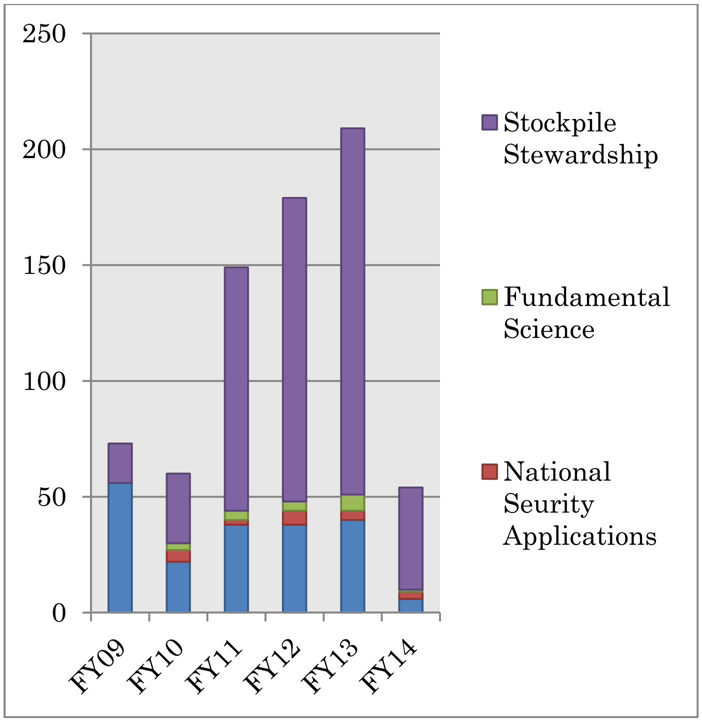

Figure 1: Summary of NIF target shots from FY2009 through February, 2014. Shots support three major user programs: Stockpile Stewardship, Fundamental Science, and National Security Applications. In addition, there are a number of shots requirement to calibrate diagnostics and new capabilities, and to qualify systems.

Figure 2: Summary of process for allocation of NIF resources. The process starts with a call for proposed experiments. After various reviews, approved experiments are incorporated into the NIF Facility Use Plan and then scheduled.

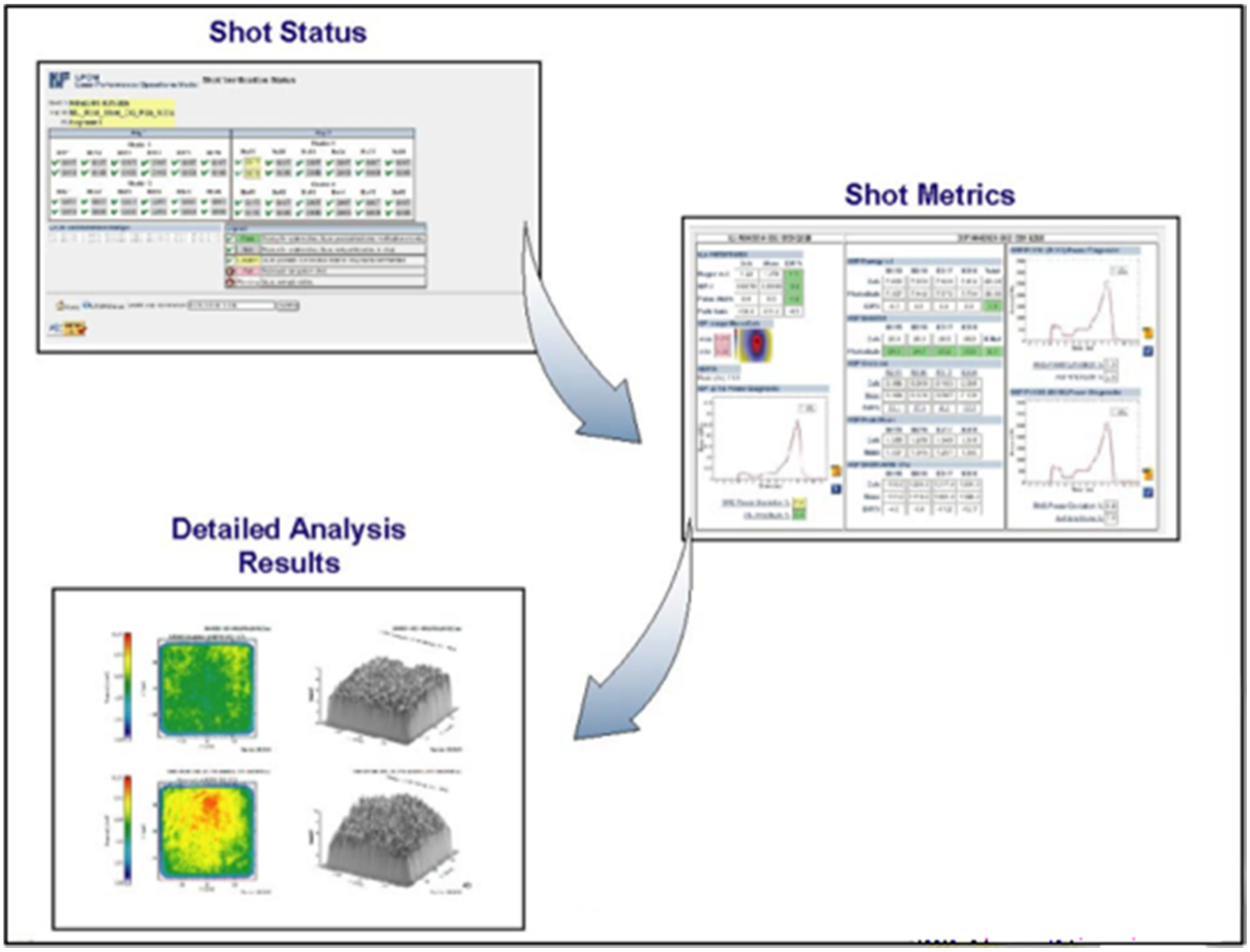

Figure 3. After each shot, a web-based format enables the detailed laser performance for any beamline to be examined using a suite of data trending and analysis tools.

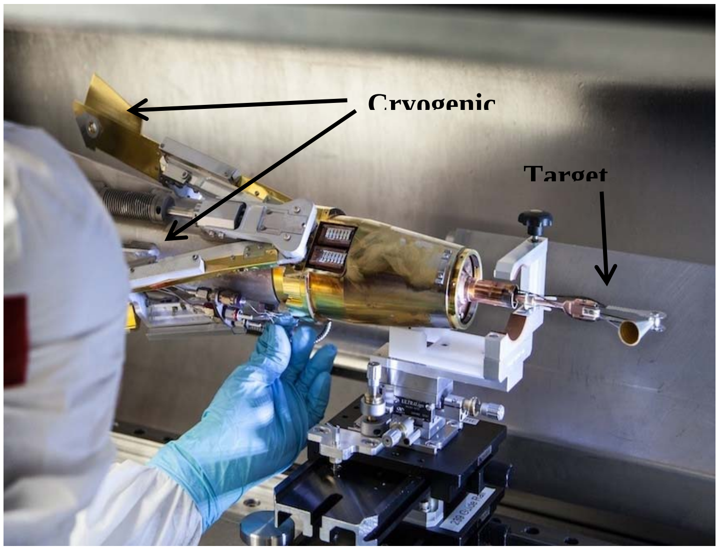

Figure 4: Installation of a cryogenic target on the TARPOS. Note that the cryogenic shields (shrouds) are retracted in this view. These will close around the target once the installation is complete, to maintain target conditions until just prior to the shot. At that time, the cryogenic shields will swing open, exposing the target to the laser beams.

Figure 5: Target Gas Manifold Operations. The gas manifolds provide a variety of gases that can be used in the targets.

Figure 6: Worker installing a diagnostic snout onto a DIM diagnostic. This operation is performed while the DIM vessel is vented to air. After installation, the vessel is evaluated and the cart holding the diagnostic snout positions it to within a few cm of the target.

Figure 7: Examples of primary (Target Bay) and secondary (Switchyard) shield doors. This view is taken in the Switchyard, with the door on the left closed at the entrance to the Target Bay, and the door on the right closed at the exit from the Switchyard to the core of the NIF building. Depending on the anticipated neutron yield of the shot, some or all of the shield doors will be closed.

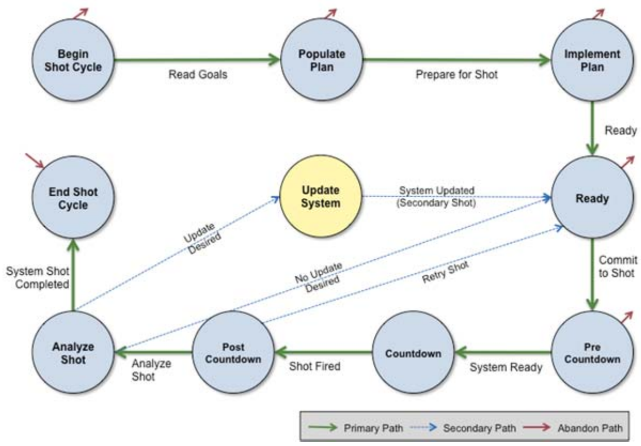

Figure 8: The NIF Shot Cycle. The primary path of the shot cycle follows the green arrows. If conditions are not met, the shot cycle can be abandoned as indicated by the red arrows. The blue arrows show alternate paths, such as "Update Desired". This would occur if the Shot Director was not satisfied with the performance of the rod shot, and adjustments are necessary.

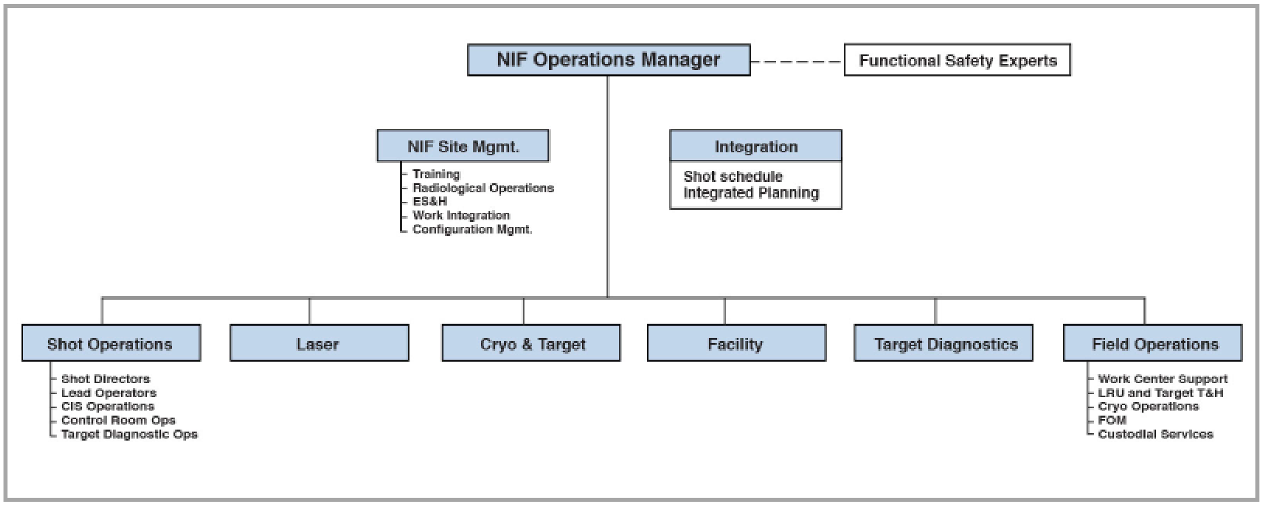

Figure 9. NIF Operations Organization.

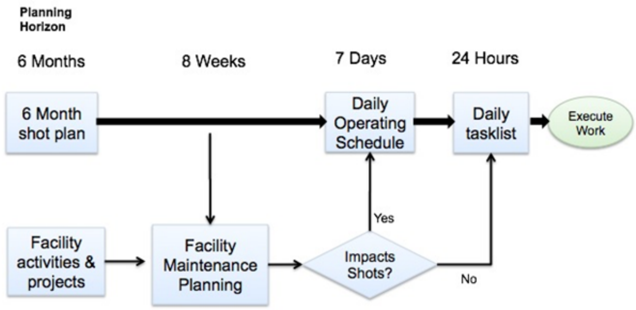

Figure 10. NIF maintenance planning process is integrated with the shot scheduling. This flow chart shows the planning horizons for facility maintenance and improvement activities. If done sufficiently in advance maintenance can be effectively coordinated with shot operations.

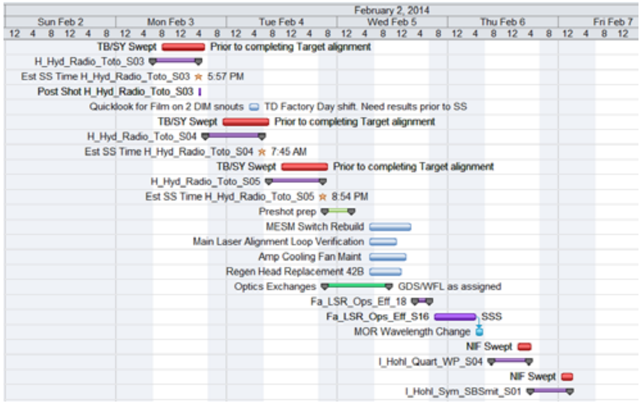

Figure 11: Example of a Daily Operating Schedule. Red bars identify stay out times for a shot. Purple bars identify the shot cycle. Blue bars identify maintenance or preparation activities.

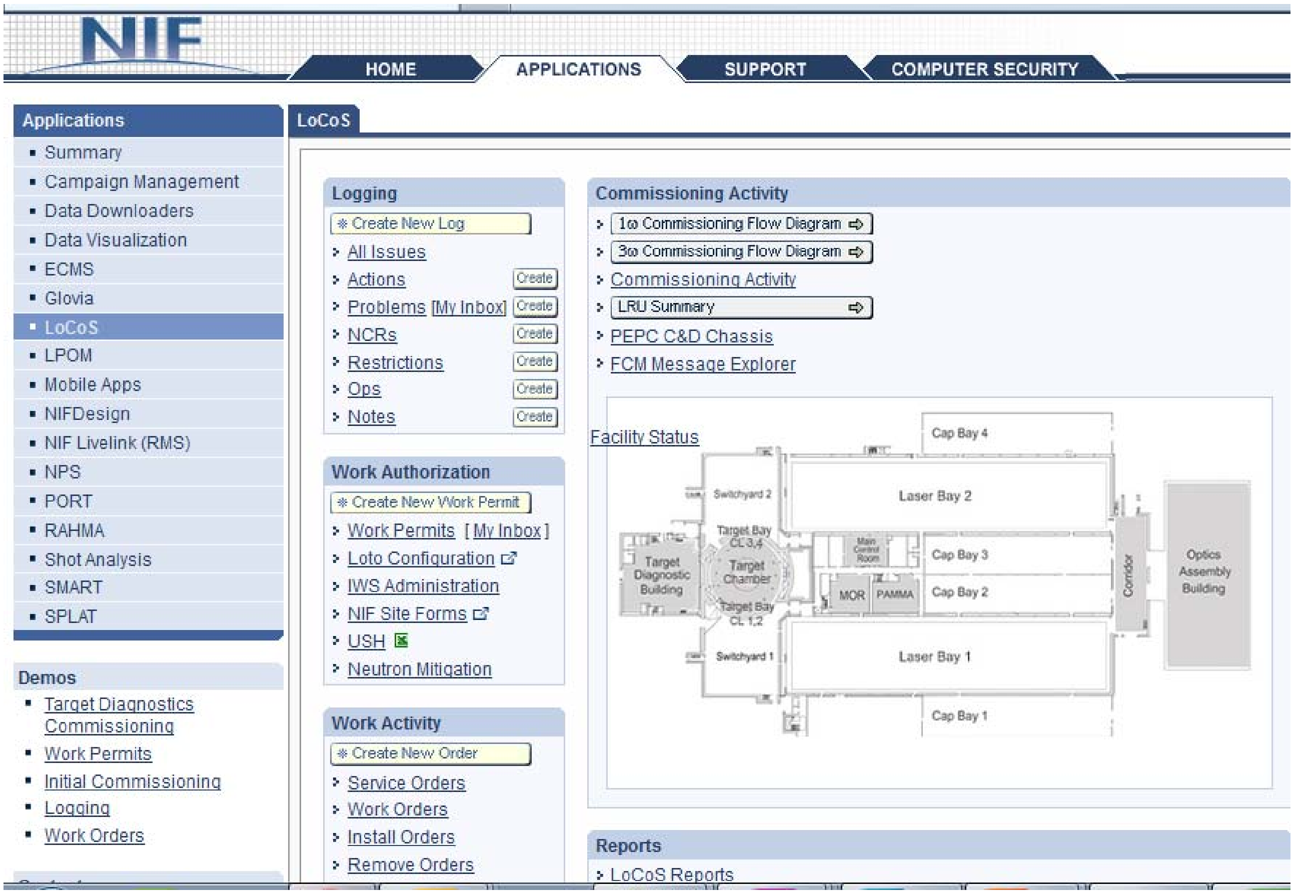

Figure 12: Screen shot of the web-based Location and Component System (LoCoS). Key applications/tools supporting NIF operations can be selected on the left. The work permit module discussed in Section III.B is found near the center of the screen shot, under "Work Authorization".

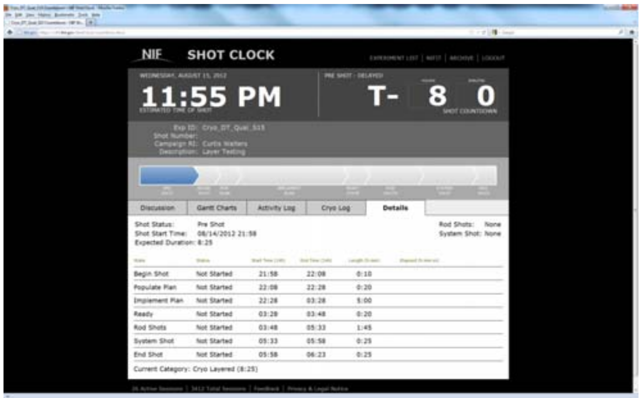

Figure 13: The NIF Shot Clock screen shows progress in the shot cycle. See Figure 8 for details of the shot cycle.

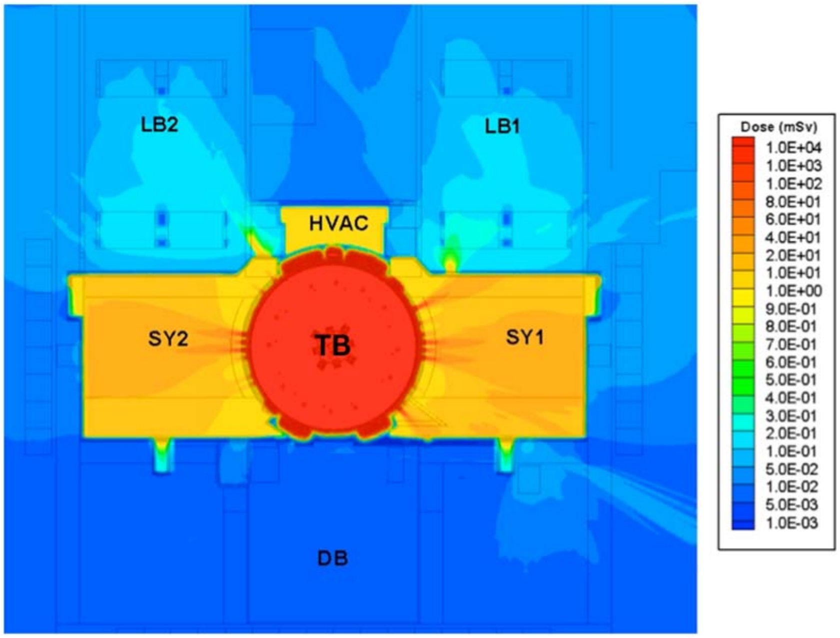

Figure 14. Prompt radiation dose map showing estimated radiation levels within the facility at ground level during a 20 MJ shot. The shielding around the facility mitigates the dose in occupied spaces both inside and outside the facility to levels < 50 μSv.

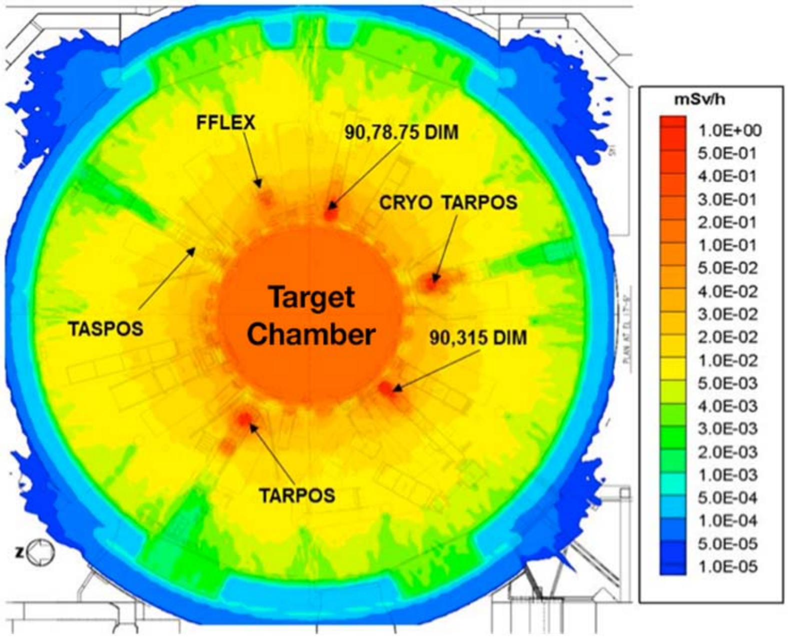

Figure 15. Decay radiation dose map showing estimated radiation levels within the Target Bay (TB, at the mid-plane) five days after a 20 MJ shot. By this time, the dose rate in most spaces within the TB has fallen below 50 μSv/h.

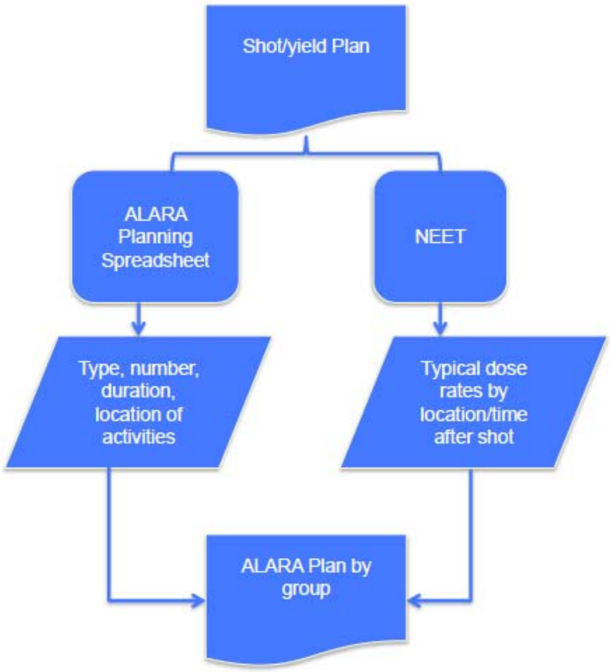

Figure 16: The ALARA Planning Process. The NEET (NIF Exposure Estimating Tool) combines predicted dose rates for a specific location after a set of shots with task duration at that location to estimate worker dose. This forms the basis for the ALARA plan for the group of workers performing a set of tasks over the year.

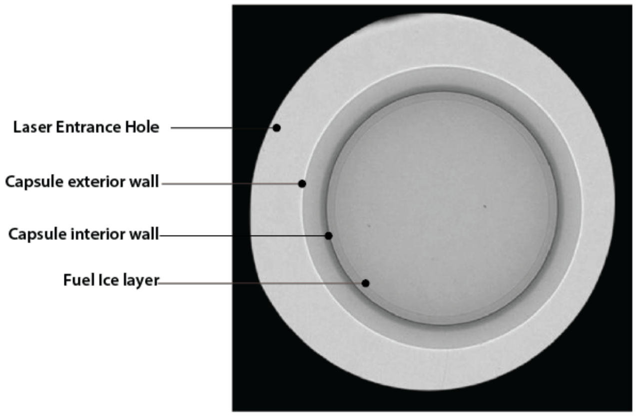

Figure 17: Phase contrast x-ray image of a fully formed DT ice layer within the target capsule. This view is through the laser entrance hole. The thin, uniform ice layer can be distinguished from the capsule. The darkening in the capsule shows the varying dopant composition in the plastic.

Table I. Summary of Key Hazards at the National Ignition Facility

Hazard	Source	Typical Mitigation
Hazardous Energy Sources	• Electrical equipment • Large volumes at vacuum • Pressure systems • Mechanical equipment	• Lockout/tagout • Venting systems
Oxygen Deficiency	• Argon used in beamtubes • Nitrogen used for cryopumps	• Containment of gases (tanks, piping) • Oxygen deficiency monitoring system and alarms • Pressure relief devices
Fire	• Electrical equipment • Combustible material	• Fire detection and suppression system • Fire barriers
Shrapnel	• Off-normal electrical events (e.g., Power Conditioning System, PCS)	• PCS module design to vent overpressure and trap shrapnel • Reinforced Capacitor Bay walls
Shrapnel and Pressure hazard	• Vacuum-loaded optic failure	• Optics designed to crack not shatter • Optics inspection system to monitor crack growth • Rupture panels on beamtubes
Laser light	• Main laser • Alignment and diagnostic lasers	• Barriers: beam blocks, shutters, laser curtains, enclosures, walls and doors • Lockout/tagout • Permissive keys
Hazardous Materials (e.g., Be)	• Target materials • Diagnostic materials	• Confinement and contamination control systems (see next section) • Contamination control practices, work permits, training, PPE
Radiation	• Target materials • Prompt and decay radiation from shots • Activation and fission products resulting from shots	• See next section

Table II. Typical Gas Fuel Specifications

Low Yield (typical)	2 atomic % D (D=deuterium)	74% T: 24% H (T = tritium; H=normal hydrogen)
High Yield (typical)	50:50 D:T	< 1% H
^{3}He In growth	< 300 hours	
Other Contaminant Gases	Methanes	< 200 ppm
	Waters	< 60 ppm
	Carbon Dioxide	< 60 ppm

Table III. List of possible Neutron Mitigation Actions for Systems in the NIF Target Bay

• Remove sensitive components, incorporate quick disconnects for easy removal before shots
• Administratively gate the alarm signal during a shot
• Replace digital sensors with an analog type.
• Relocate to take advantage of the natural shielding of the building
• Replace Liquid Crystal Display (LCD) panels with Light Emitting Diodes (LED) backlit panels
• Replace solid state electrical ballast with a transformer type electrical ballast
• Separate the battery and control circuit from the load
• Use analog tube camera systems and some sacrificial higher resolution Charge Coupled Devices (CCD) cameras.